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ROAD MAP TO BUILD CIVIL ENGINEERING STRUCTURES ON THE MOON - AN OVER VIEW

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Abstract: This paper broadly deals with various strategic steps involved in realizing Civil Engineering Structures on the Moon. Utilization of local regolith should form main strategic criteria towards building the Moon village. All static and dynamic properties of lunar soil need to be evaluated to workout comprehensive building models in order to withstand environmental forces like temperature extremes, meteoroid impact, ionic bombardments and vacuum conditions (i.e. no air). Besides these, one need to consider moonquakes along with 1/6th “g” condition for dynamic stability. A few schematic structural profiles are also indicated in this technical paper.

Keywords: Regolith, Moonquakes, Static and dynamic properties, Structural stability, Impacts, Cohesion.

1. INTRODUCTION

Since prehistoric times the Moon is the brightest object in night sky after the Sun, whose desolate beauty has been a source of fascination and curiosity for the mankind since ages.

International Space Community is planning a broad range of human and robotic missions including ***the Moon, Mars and destinations beyond***. The President of the U.S.A has once described **“*this space program is not as a race, but as a journey in which all nations are invited to participate for the benefit of mankind….”.*** Establishing an extended human presence on the Moon could vastly reduce the cost of future space exploration projects. Further *Lunar bases* will be very much useful for the spacecraft to be launched deep into space due to the “reduced gravity” and “lesser escape velocity”. Essentially this involves technical expertise and knowledge to initiate **civil engineering planning and construction activities** on surface of the Moon to enable future human settlement i.e. for Moon colonization.

2. RELEVANCE OF THE MOON EXPLORATION

The international space community believes lunar exploration is the first step towards interplanetary missions with the following objectives

- To realize Moon colonization with extended presence of humankind
- To pursue scientific activities to address history and formation of the Moon and Solar system
- To test advanced technologies and exploration techniques as a bench mark for the future interplanetary missions to Mars, Venus and beyond.
- Also it helps in global partnership and co-operation among the countries in pursuit of common objectives
- To explore the possibilities of using the rare materials and minerals available on the Moon surface for economic expansion.

2.1 Broad Design Philosophy:

Most of the essential materials required for construction of permanent lunar bases need to be produced from the resources available on the Moon surface itself in order to avoid the need for transportation of building materials from the Earth. The foremost requirement of futuristic lunar structures will be to anchor such buildings into the lunar regolith, which is a surface stratum for a depth of 1 to 2 km.

Thus the lunar regolith forms as a very important criterion for understanding of the Moon & space environment around it. Detailed study and characterization of Lunar Soil will enable

- To predict the behavior of foundations on lunar surface
- To explore the possibility of using the lunar soil for preparing futuristic building materials for creating Moon villages

To understand chemical/ mineralogical composition of regolith along with its geo-technical & mechanical properties.

3. BRIEF SUMMARY OF LITERATURE:

Survey of technical literature since last four decades reveals various *conceptual ideas, schemes and proposals* have been put forth by multiple infra-structural and geo-technical engineers/scientists hailing from space agencies and academic institutions from advanced countries like USA, China, Japan, Tukey, Canada & Russia etc., These conceptual schemes can be broadly categorized as **inflatables, erectables, lunar concrete structures, using existing lava tubes, reusing rovers** as **bases of settlements, using Geo-synthetics applied Lunar structures and finally habitats made with cast regolith etc**

Every possible option has got its own merits and demerits considering the need for the transportability of such materials from the Earth, feasibility of constructional processes and economic considerations etc., However, this technical paper focuses on usage of available lunar regolith as parent material for building blocks with structurally viable shapes and profiles considering various environmental forces. Regolith can be studied as a possible building material to take care of super structural requirements by understanding its complete behavior under axial compression, tension, shear and flexure. This requires adoption of suitable binders /resins / epoxies as matrix material to assign the property of "*bindability".* For human survival, the internal pressure within the habitant structures will be invariably positive i.e. greater than the external vacuum. Hence the shapes of the structural modules have to be **"concave downwards" (Like saddles)** so that, the building material is predominantly stressed under compression as a funicular shell member. This needs innovative structural frame designs also.

A detailed scientific study of lunar regolith helps us to understand and quantify the attenuation levels against radiations/ ionic bombardments and also the extent of insulation against extreme temperature variations. This data can help us to use local regolith as safe material for proposed cushioning bed or as a merlon. However, robotic engineering needs to be extensively used for making building blocks and also for erecting required structural frame works of different geometrical shapes

4. LUNAR BUILDING MATERIALS:

The construction industry requires different types of building materials which have to be strong in Compression/Tension/Shear& Flexure to withstand different stress resultants caused by the self-weight & applied

or imposed loads of the structure. Apart from the above Engineering strength properties, the materials should also be durable enough to resist wide variation of temperatures ranging from -150 degree Celsius to +107 degree Celsius as per lunar climatic conditions. Further, these materials should also be able to withstand bombardment by meteoroids along with radiation effects. In addition to the above, lunar materials and structures should optimally resist the dynamic stresses caused by moonquakes and also mechanical impacts transferred by continuous bombardment by asteroids and meteoroids. There are no other environmental forces like wind/rain/ glaciations on the Moon. However, lunar gravity of 1/6th “g” contributes towards self-weight of various structural and nonstructural members.

4.1 Need for Study of Soil Simulants:

The above technical requirements need extensive analysis/design and research work involving “large quantities of lunar regolith” pertaining to either High land or Mare land of the lunar surface. *But unfortunately the amount of lunar regolith brought back to the Earth from various lunar missions is too less to be used for such engineering experiments*. Therefore, there is a compelling need to develop and produce bulk quantities of **LUNAR SOIL SIMULANT (LSS)** which can be advantageously used for various research works, which in turn can help us to workout design methodology and criteria for material specification for “Moon village” development.

4.2 Lunar Soil Simulation Studies:

In this regard a pioneering work has been initiated by ISAC-ISRO, India to establish a Lunar Terrain test facility(Fig.1 to 4) to simulate the Lunar conditions with respect to soil/ambient temperatures & light lux levels etc., and also $\frac{1}{6}$th *“g”* conditions.

Fig. 1. Simulation Studies in Terrain Test Facility

Fig.2. Rover on Lunar Soil

Fig.3. LSS Sample quality check at Pulverization unit

Fig.4. Quality checking of simulant particle size using manual sieve sets

Fig.5. Investigator examine the outcrop location

Chandrayaan-2 mission of India with indigenously developed Orbiter, Lander & Rover are scheduled to land in the lunar polar region in Dec-2017 where the terrain composition is believed to be closer to the highland composition. So the lunar soil simulant which has been indigenously generated and co-patented by ISRO and Periyar University, Selam has been simulated with "high land soil" with respect to chemical and mineralogical compositions apart from geo-mechanical properties.

4.3 Status of R&D Works done so far:

Indian geologists have identified that Anorthosite rock belts (Fig.5) available at certain places near to Salem, Tamilnadu, India almost simulate with respect to Mineralogical & Composition of actual anorthosite rocks of Lunars Regolith. A scientific process has been adopted to prepare bulk quantity of lunar soil simulant from these rock minerals where in various geo-mechanical properties have also been simulated by pulverizing the rock samples into the grains of gradation ranging from 30microns to 1000microns. Such graded samples have been mixed in certain specified proportions so that the required geo-mechanical properties have almost tallied.

4.4 Material Specifications:

Proportioning of soil grains were done in order to produce the particle size distribution similar to that is seen in retrieved lunar soil samples brought from Apollo missions.

Tab. 1. Comparison of Mineralogical Composition of LSS

Sl.No.	Availability of Mineral	Approximate % in lunar soil simulant of ISRO	Percentage in actual lunar soil
1.	Plagioclase	81-95	80-91
2.	Pyroxene	1-9	4-20
3	Olivine	1-5	1-10
4.	Others	3	3

Tab. 2. Comparison of Chemical Composition of LSS

S.No.	Availability of Mineral	Approximate %age in Lunar Soil Simulant – (based on Anorthosite rocks)	Percentage in actual lunar soil
1.	SiO_2	43-46	44-46
2.	Al_2O_3	21-31	21-36
3.	CaO	15-18	14-18
4.	Others	7-20	8-19

4.5 Evaluation of Geo-Mechanical Properties of Lunar Soil Simulants:

It is necessary to study the behavior of the regolith material with respect to compressibility/settlement & shear strength (due to cohesion and internal angle of friction) so that we can analyze, design and detail the necessary foundations for lunar structures. In this connection, the following geo-mechanical properties of LSS were evaluated with suitable proportioning of various gradations/fine particles so that the values obtained are well within the acceptable range as listed below.

Tab. 3. Comparison of Geo-Mechanical Properties of LSS

Soil property required for Foundation design	**Range of actual value of Apollo-1 soil sample**	**Value of lunar soil simulant.**
Cohesive module of deformation kc (N/m^{n+1})	*1400 (Approximate)*	*1030*
Frictional module of deformation kp (N/m^{n+2})	*820000 (Approximate)*	*822559*
shrinkage exponent, n	*0.8 to 1.2*	*1.03*
Cohesion Stress, c(N/m^2)	*100 to 1000*	*353*
Angle of internal friction (deg)	*30 to 50*	*37 deg*
Shear deformation modulus (m)	*0.0178 (Approximate)*	*0.0143*
Bulk density, (kg/m^3)	*1500.0 (Approximate)*	*1475*

4.6 Details of Experimentation

Extensive soil sample testing has been carried out at Dept. of Civil Engineering, National Institute of Technology, INDIA to evaluate various technical parameters as listed above. Experimentations have been carried out on large number of soil simulant samples with different percentages of mixing of various gradations. A few important testing data obtained along with relevant graphs and correlations are presented herewith for reference and academic interest.

COHESION STRESS(c), ANGLE OF INTERNAL FRICTION (ϕ), SHEAR DEFORMATION MODULUS (k):

Shear strength parameters (cohesion and friction angle) are mechanical parameters of a soil that have profound influence on ultimate bearing capacity, slope stability, and trafficability. The most common way to characterize the shear strength of a soil is the Mohr-Coulomb failure criterion, which can be expressed as:

$$\tau = c + \sigma.\tan \varphi \tag{1}$$

Where τ is the shear strength at failure on the failure plane, σ is the normal stress on the failure plane; c is the cohesion of the soil, and φ is the internal friction angle.

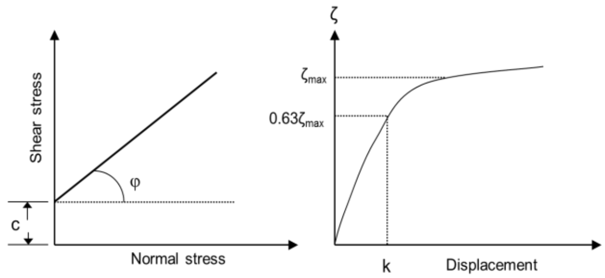

Fig.6. Graphical representation of Coulomb equation

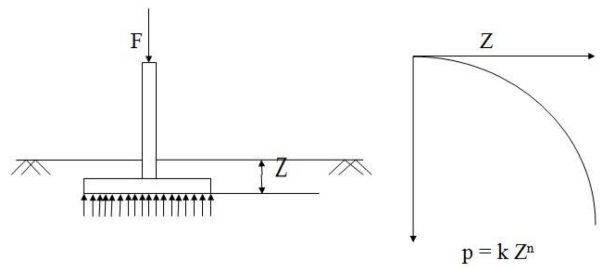

Fig.7. Schematic view of load settlement plot

$$\mathbf{P= (kc/b + k_{\varphi})\, Z^{n}} \tag{2}$$

$$n = \frac{\sum p2 \sum p2 \ln p \ln z - \sum p^2 \ln p \sum p^2 \ln z}{\sum p^2 \sum p^2 (\ln z)^2 - \left(\sum p^2 \ln z\right)^2} \tag{3}$$

$$\ln k = \frac{\sum p2 \ln p - n \sum p2 \ln z}{\sum p^2} \tag{4}$$

Where,
K= Modulus of inelastic deformation and
n= Sinkage of exponent
p= Pressure
Z= Soil depth
k_c & k_φ = modulus of deformation with respect to cohesion and friction.
lxb = Size of the test plate

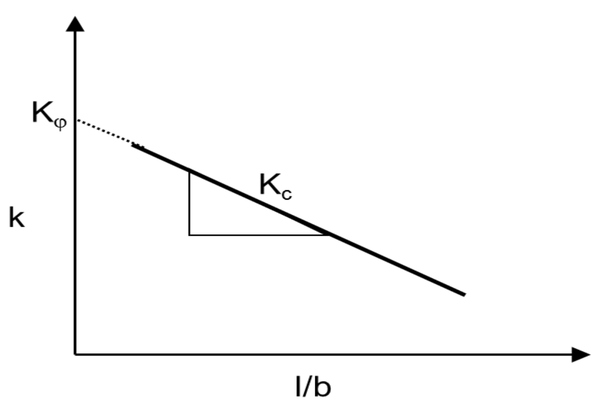

Fig.8. Determination of k_φ and k_c value

Dept. of Geology, Periyar University, Selam, India has supplied five gradations of Anorthosite soil samples which has a particle size ranges from 30µm - 1000µm. These Anorthosite soil samples were tested by mixing in different mix proportions.

Tab. 4. Lunar Soil Simulant Samples (LSS)

Soil sample	Grain size (µm)
Sample 1	30-80
Sample 2	80-150
Sample 3	150-300
Sample 4	300-600
Sample 5	600-1000

4.6.1 Shear Property of LSS

Direct shear method is used to determine the angle of internal friction (φ), cohesion (c) and shear deformation modulus. A typical direct shear test result is shown in Fig.9.

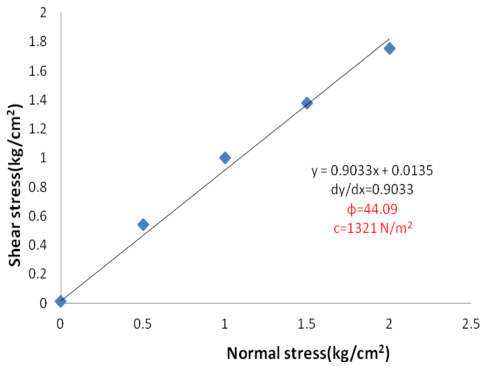

Fig. 9. φ and c value for one of soil samples

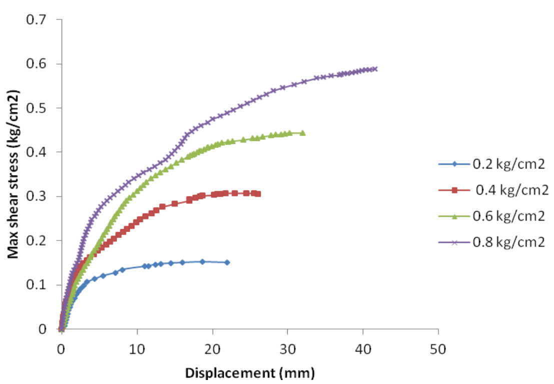

Fig.10. Shear stress vs Displacement for LSS Samples medium scale direct shear test)

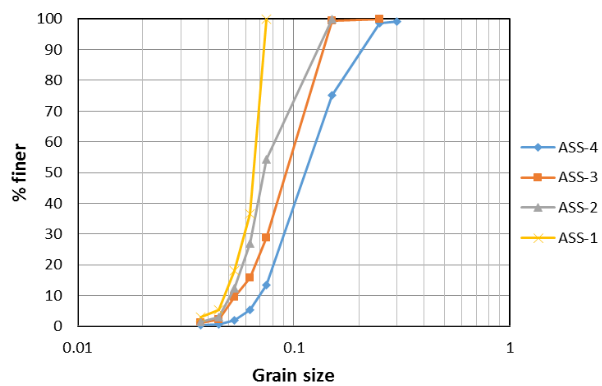

Fig.11. Grain size distribution of different (from mix proportions.

Fig.10 shows the relationship between shear stress and corresponding shear deformation for varying normal stresses (0.2 kg/cm² to 0.8kg./cm²).

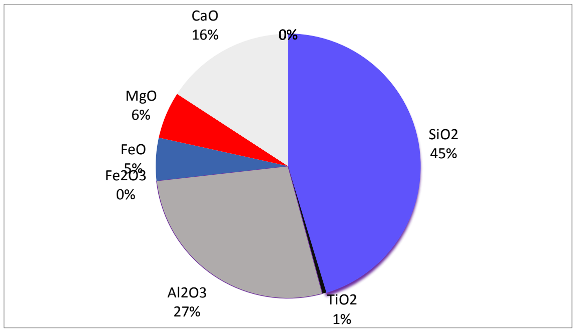

Fig.12. Apollo-16 lunar high land soil sample – Chemical composition

Fig.13. Close-up of an Astronaut boot print taken on Apollo 12. It is one half of a stereo pair. The field of view is approximately 50mmx50mm. (relative density seems to be medium stiff)

4.7 Study of Advanced Properties of LSS

ISRO in collaboration with premier academic institutions like Indian Institute of Science, Bangalore, National Institute of Technology, Trichy has planned to take up further studies on lunar soil simulants by evaluating various dynamic properties like Damping co-efficient of soil, Modulus Elasticity (including shear modulus) Poisson's Ratio, Soil compression capability, Plastic yield stress, Hydrostatic stress verses volumetric strain curve, Dilation angle, Flow stress ratio etc for conducting numerical simulations using finite or discrete element analysis etc.

The above dynamic properties will enable us to understand the behavior of lunar regolith under sustained vibration loads caused by launch of space vehicles from the futuristic lunar launch pads, behavior of futuristic roads and pavements on the Moon or under the tracked vehicles like passenger rovers etc., and also the dynamic response of lunar structures under effects of moonquakes.

5. CHOICE OF BUILDING BLOCKS:

The lunar environment has got extreme temperature variation ranging from as low as -150 degree Celsius to as high as +107 degree Celsius-hence we have to process and devise a suitable building material which can be used to withstand such extreme environmental conditions. It may be therefore technically advisable to take up necessary research works by using lunar soil simulant itself for making **strong building blocks** with suitable additives like polymers/epoxies/resins which can impart strength as well as environmental durability apart from dimensional stability.

- In this regard, a robotic mechanism also need to be developed- which should be able to process and produce the designed building blocks by using the actual lunar regolith on the Moon surface similar to production of soil block masonry units on the earth surface.
- Specially designed *light metal alloy frame work modules* of Aluminum or *space qualified metals* etc can be fabricated and transported to Moon which can be used for erecting of structural work.

5.1 Recommended Profiles of Lunar Structures

- On similar lines, funicular shaped floor profiles can also be designed (Conceptual schematic diagrams are presented in fig numbers 14A to 18B) which can be easily assembled on Moon to erect curved slab panels in modules of size say 2m X 2m, so that required size of floor layouts can be realized. The funicular shape is preferred in view of its structural behavior under net downward gravity loads - which causes only compressive stresses and no tensile stresses therefore no risk of cracks (in view of vacuum conditions

outside and internal pressurized requirements inside the net load intensity on the membrane structures is expected to be minimum).

- The filling screed media can be of lunar regolith itself with necessary spray binding chemicals which can impart necessary intra-particle bonding. From the available literature pertaining to cohesion, friction and shear strength of lunar regolith, it appears to be technically feasible to make necessary *cast-in-situ slab panels*, which can have adequate flexural strength.
- A specially processed and manufactured PVC sheets with self-adhesive properties can be thought of using as protective coatings for external walls and roof slabs, in addition to ***as floor finishing items*** inside the structure.

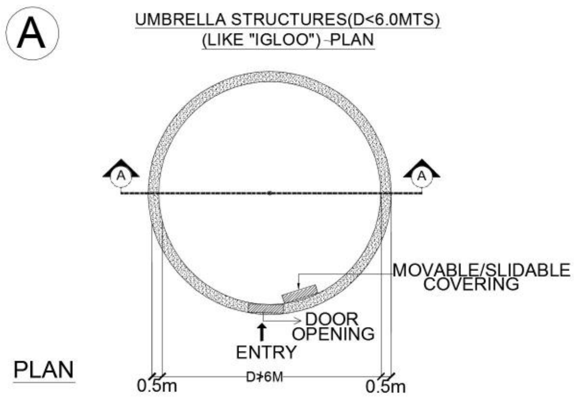

Fig.14A

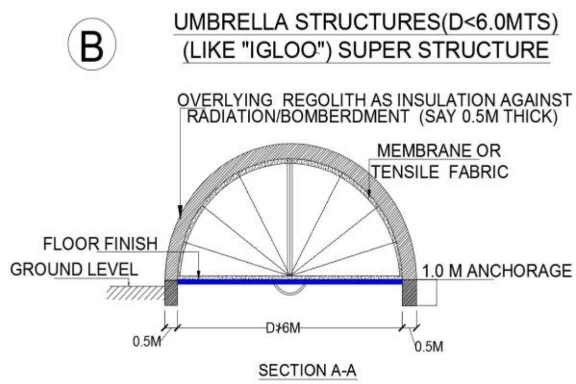

Fig.14B

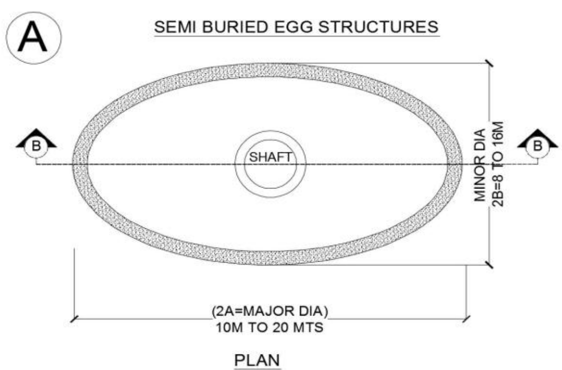

Fig.15A

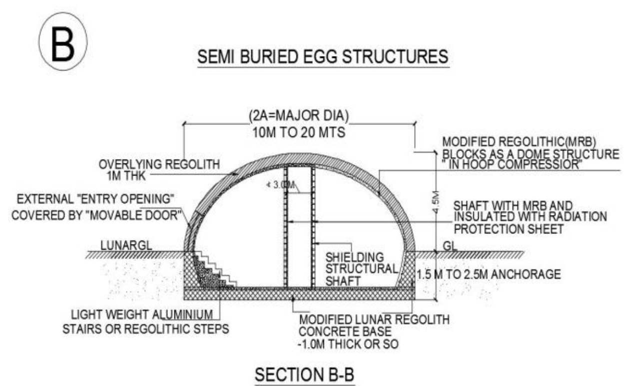

Fig.15B

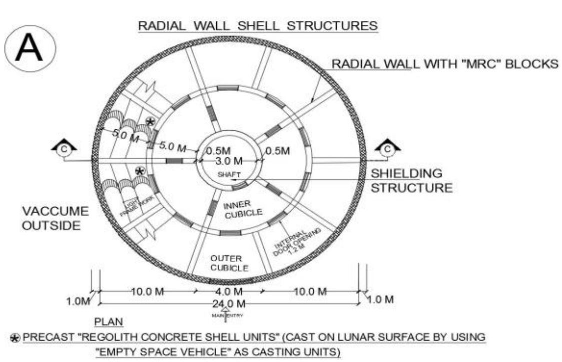

Fig.16A

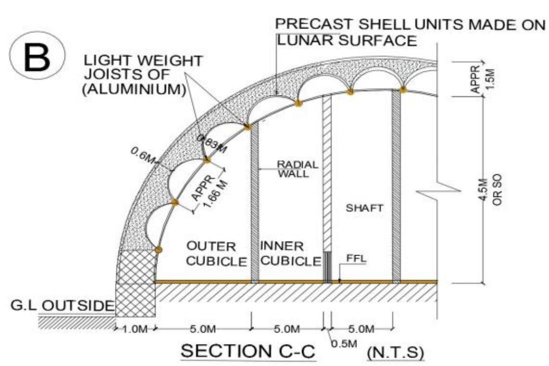

Fig.16B

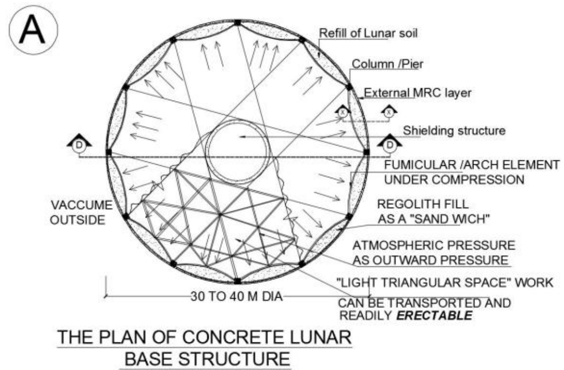

Fig.17A

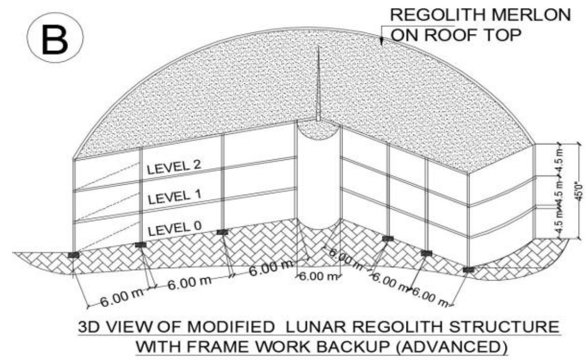

Fig.17B

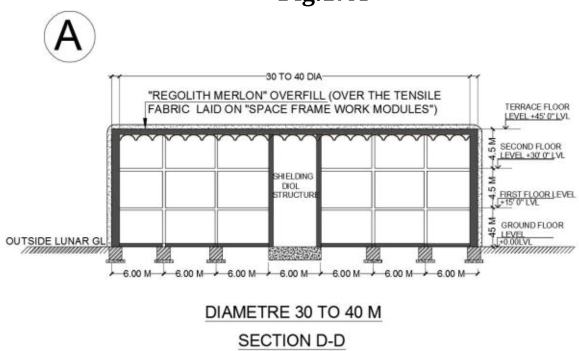

Fig.18A

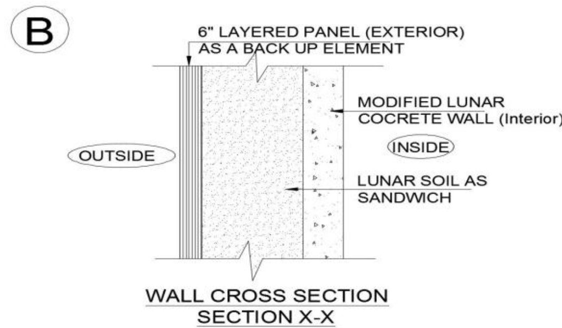

Fig.18B

5.2 Proposed Simulation Studies:

Different profiles of lunar structures are intended to be tested for likely environmental forces (like temperature, pressure variations, dead weight etc.,) by "scaled down models" using additive manufacturing technology (i.e. 3D printing) and the stress values will be compared with theoretical FEM/DEM analysis results.

6. LOAD ANALYSIS:

The proposed lunar civil engineering structure needs to be analyzed for self-weight (i.e. 1/6th of its equivalent weight on the Earth) apart from other expected super imposed loads caused by regolith Merlon cushion. The usual live loads are expected to be minimum due to less movement of a few astronauts here and there.

- In absence of atmosphere, no *lateral wind loads* are expected hence structure should be predominantly designed to withstand vertical loads which are caused by reduced self-weights and likely minimum imposed live loads.
- Special studies need to be taken up to understand the effect of ionization / charged particles on the proposed new building materials of civil engineering structures i.e. other than lunar regolith based.
- As of now, no authentic information with regard to behavior of proposed lunar structures under the effect of moonquakes is available, which needs to be evaluated with suitable simulation studies.
- In essence, a *single story* structure designed for earth terrestrial conditions should be able to withstand loads caused by equivalent *six storied* structure on lunar surface due to 1/6 g effect. This may obliviate the need for "strong soils on the Moon" due to 1/6th reduction in the soil pressure.
- From the above loading criteria, it is inferred that lunar civil engineering structures are likely to be *thin, sleek and elegant* due to 1/6th of gravity of loads and also no lateral loads either by wind or cyclone.

7. DESIGN CRITERIA:

The building materials like *"lunar regolith building blocks" (LRBB), special alloy reinforcing steel, bonding spray, required additives, adhesives, protective coatings like special PVC sheets* etc., need to be qualified for almost 1/6th of equivalent engineering strength on the Earth, but for adverse environmental conditions like temperatures ranging from -150 degree Celsius to +107 degree Celsius. The other important design criteria for the stability of the structure shall be anchoring of the foundations into deep regolith mass-for which detailed study of LSS is to be taken up on a larger scale for wider applications.

8. EVALUATION OF POST CONSTRUCTIONAL PERFORMANCE:

In the absence of atmosphere/humidity (moisture?) on the Moon surface, we need to evaluate short term and long term settlement characteristics of civil structures under the conditions of sustained loadings especially when they have to be founded into the deposits of regolith.

By using peripheral reference poles, the settlement of structure (if any) can be monitored and studied by using strain gauges/deflectometers mounted at strategic critical points on the structure for further Research and Developmental work. In this regard, the phenomenon of time bound responses like creep deflections of superstructures, consolidation of substructure etc., will give a measure of environmental impact.

9. CONCLUSIONS

In conclusion, the present technical paper makes an attempt to highlight the need to take up research works in various fields of civil engineering apart from other pure sciences & other engineering disciplines to come out with innovative design plans/concepts and execution strategy for realizing various types of civil engineering structures on the Moon in order to *herald a new (inter)planetary engineering.*

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